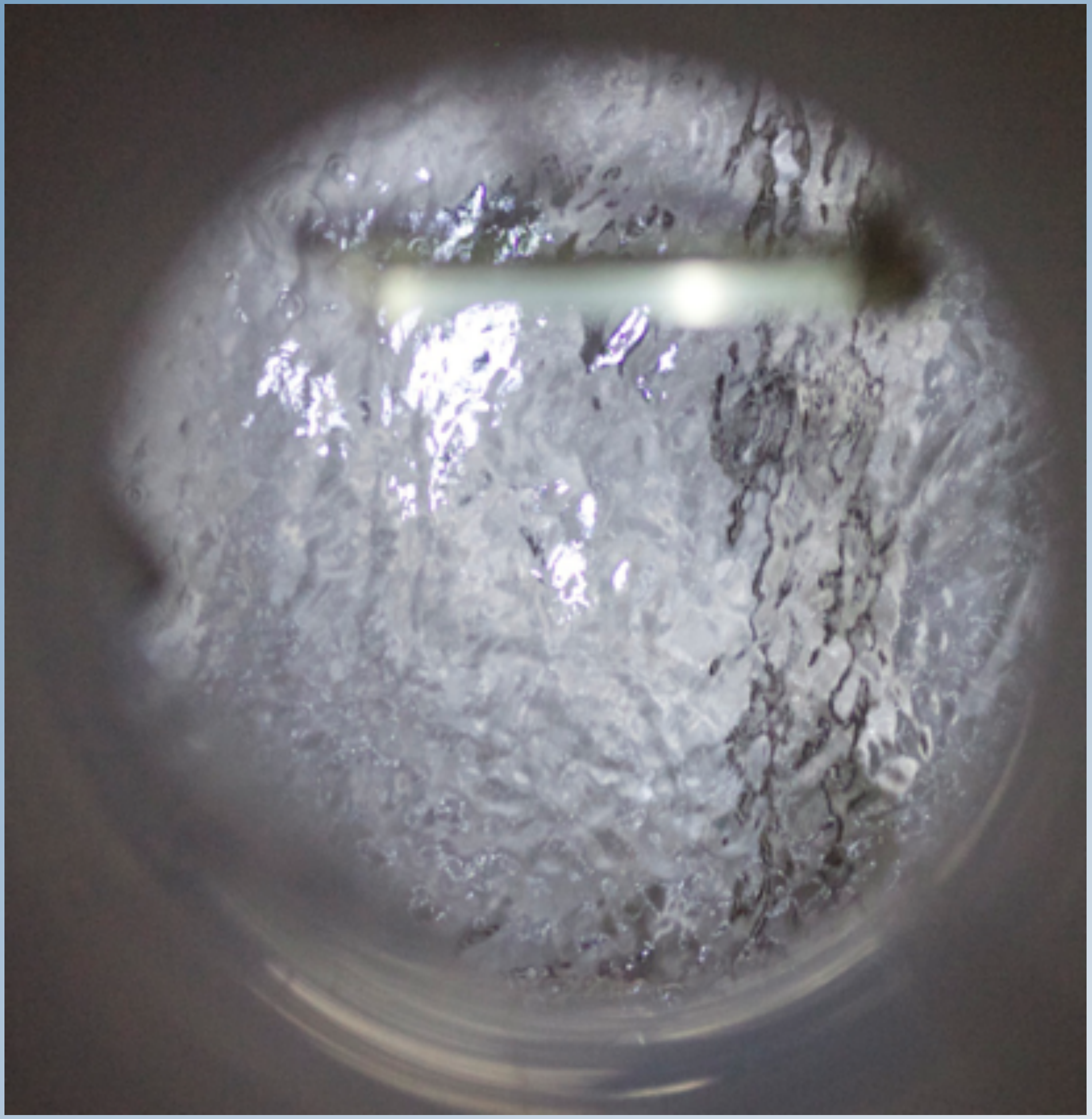
Liquid Argon Detector Development

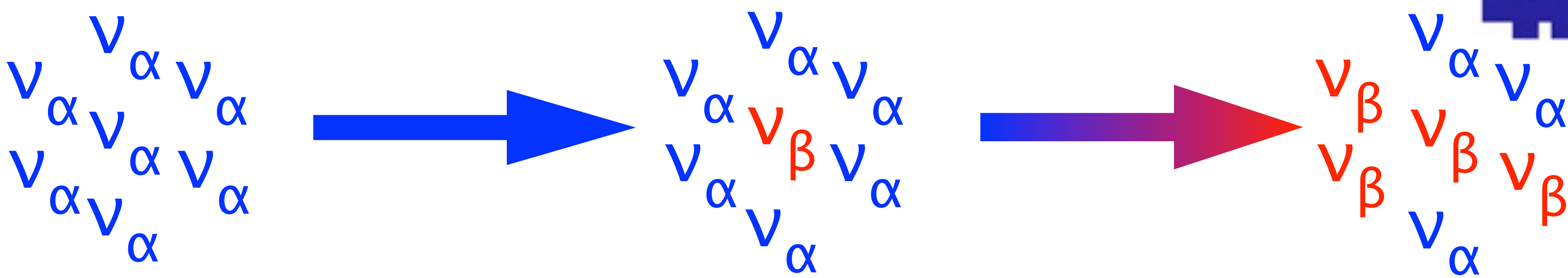


Brian Rebel
June 2012

Outline

- Neutrino Oscillations
- Introduction to liquid argon time projection chambers
- Liquid argon purity
- Electronics
- Cryostat construction
- Calibration

Neutrino Oscillations



- Neutrino oscillations are the process of neutrinos of one flavor changing to another and then back again

- Oscillations occur because the neutrino flavor states are actually combinations of neutrino mass states
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{bmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

- U is the unitary matrix that represents the rotation from the mass basis into the flavor basis

- Neutrinos interact in the flavor states, but propagate in the mass states

What We Know About Oscillations

- Zero point of mass scale currently unknown
- A variety of experiments (solar, reactor, atmospheric) have shown us
  - Atm→Δm^2 = 2.3 x 10^{-3} eV^2
  - Solar→$\Delta m^2 \approx$ 8 x 10^{-5} eV^2
- Figure shows the fraction of flavor states in each mass state
- Most mixing angles are large

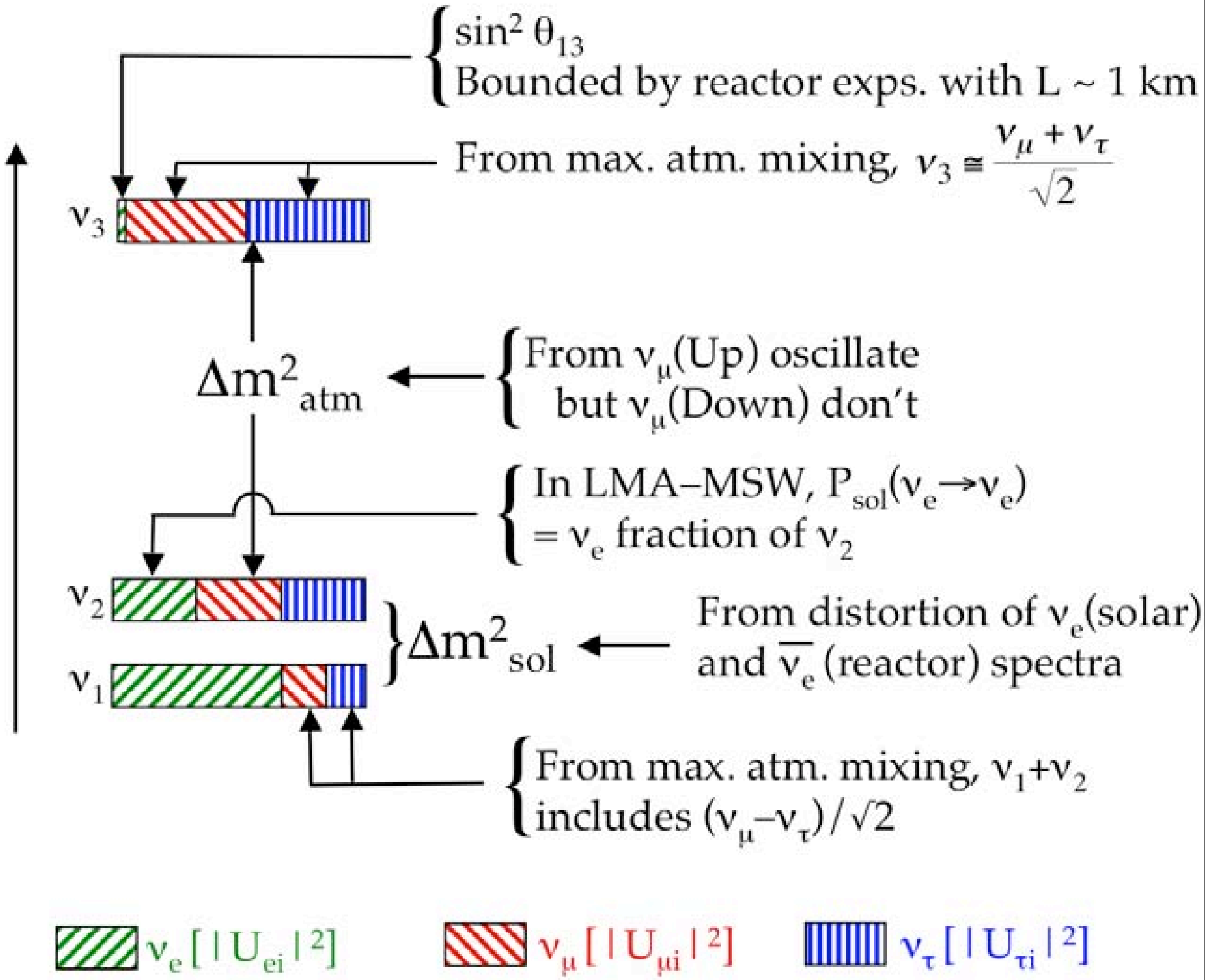


Figure from B. Kayser (2004)

What We Know About Oscillations

- Zero point of mass scale currently unknown
- A variety of experiments (solar, reactor, atmospheric) have shown us
  - Atm→$\Delta m^2 = 2.4 \times 10^{-3}$ eV^2
  - Solar→$\Delta m^2 \approx 8 \times 10^{-5}$ eV^2
- Figure shows the fraction of flavor states in each mass state
- Most mixing angles are large

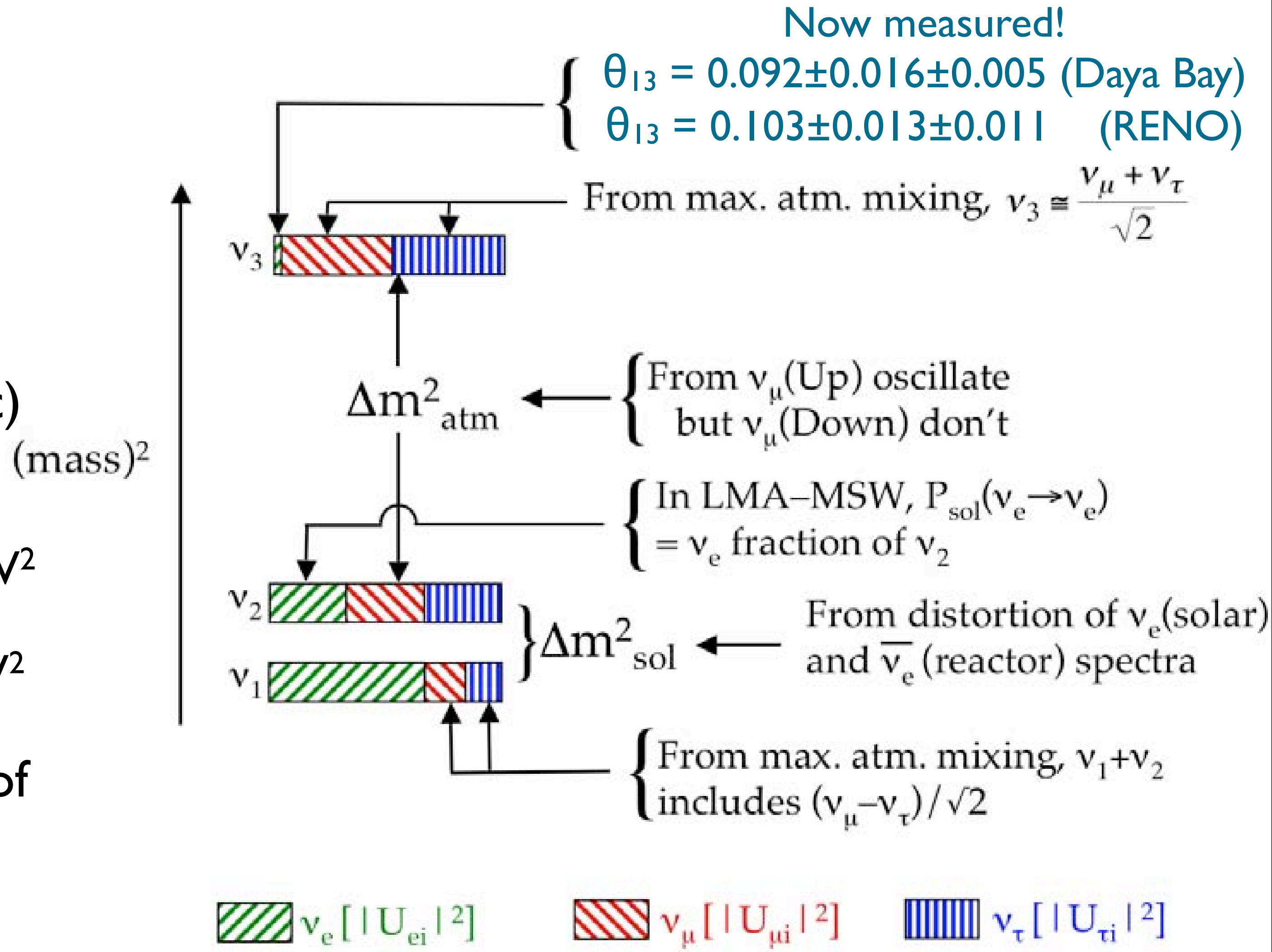


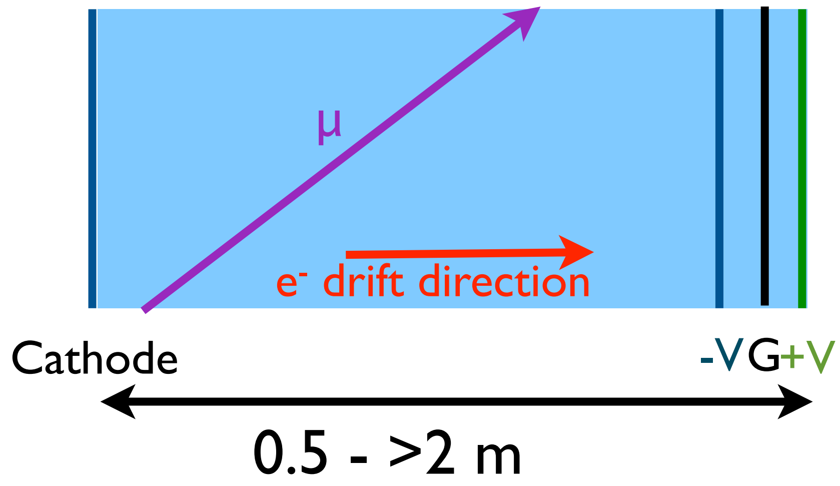
Figure from B. Kayser (2004)

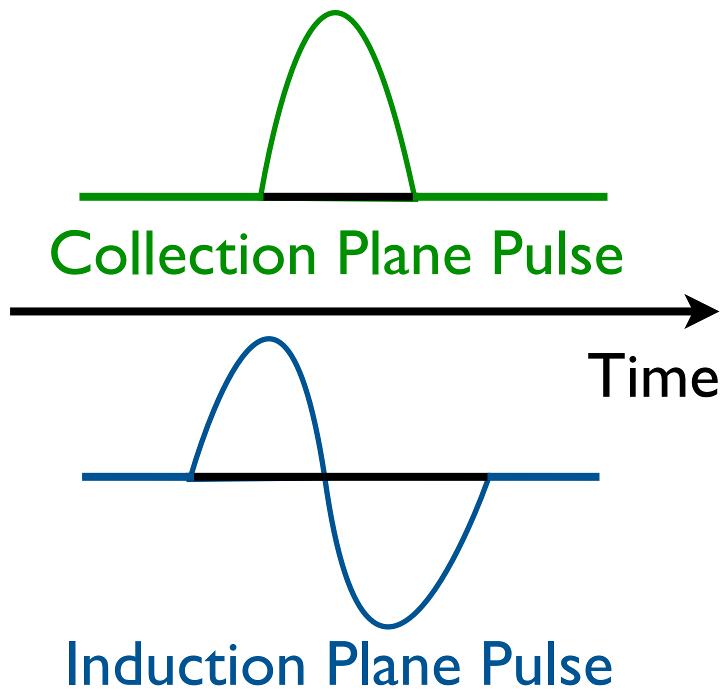
What Next?

- Future questions to answer about oscillations
  - Is the PMNS matrix sufficient to explain oscillations?
  - Are there more neutrinos than the 3 active flavors?
  - Is the CP violating phase non-zero?
  - What is the mass hierarchy?
- Most of these questions will require new experiments to answer them

LAr TPCs

- Electric field established between cathode and readout planes
- Minimum ionizing particle releases 55k e/cm
- Electrons drift toward readout planes with velocity of 0.155 cm/μs - need > 1.6 ms for 2.5 m drift
- ⟨dE/dx⟩ for minimum ionizing particle is 1.519 MeV cm^2/g
- Attractive detector design for large detectors as channel count goes as fraction of the area rather than volume
- Primary challenge - keeping LAr pure over long drift distances





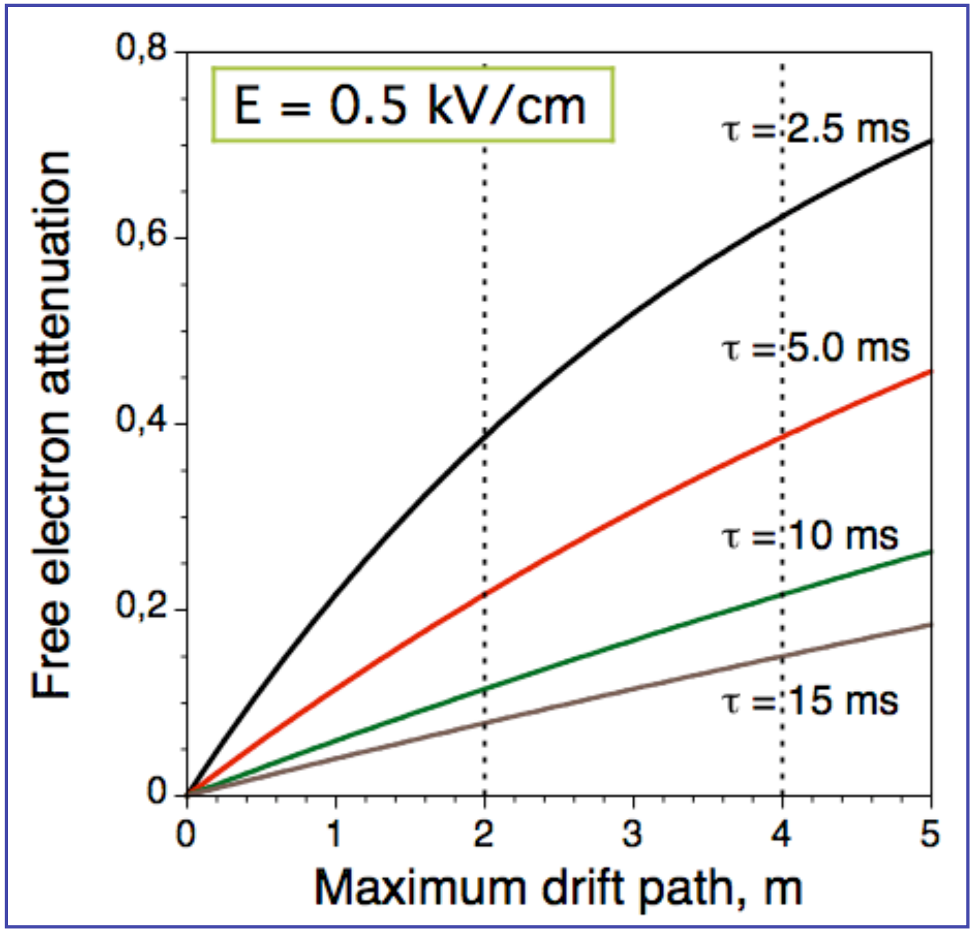
Why Argon?

	Water	He	Ne	Ar	Kr	Xe
Boiling Point [K] @ 1atm	373	4.2	27.1	87.3	120.0	165.0
Density [g/cm^3]	1	0.125	1.2	1.4	2.4	3.0
Radiation Length [cm]	36.1	755.2	24.0	14.0	4.9	2.8
Scintillation [γ /MeV]	-	19,000	30,000	40,000	25,000	42,000
dE/dx [MeV/cm]	1.9		1.4	2.1	3.0	3.8
Scintillation λ [nm]	475	80	78	128	150	175

- Cheap and easy to obtain - 1% of atmosphere, $1 / L (cheaper than Pepsi)
- Relatively high boiling point
- Produces lots of scintillation light as well as ionization
- Transparent to own scintillation, useful for triggering
- Good liquid for having large electric field running through it

LAr Purification

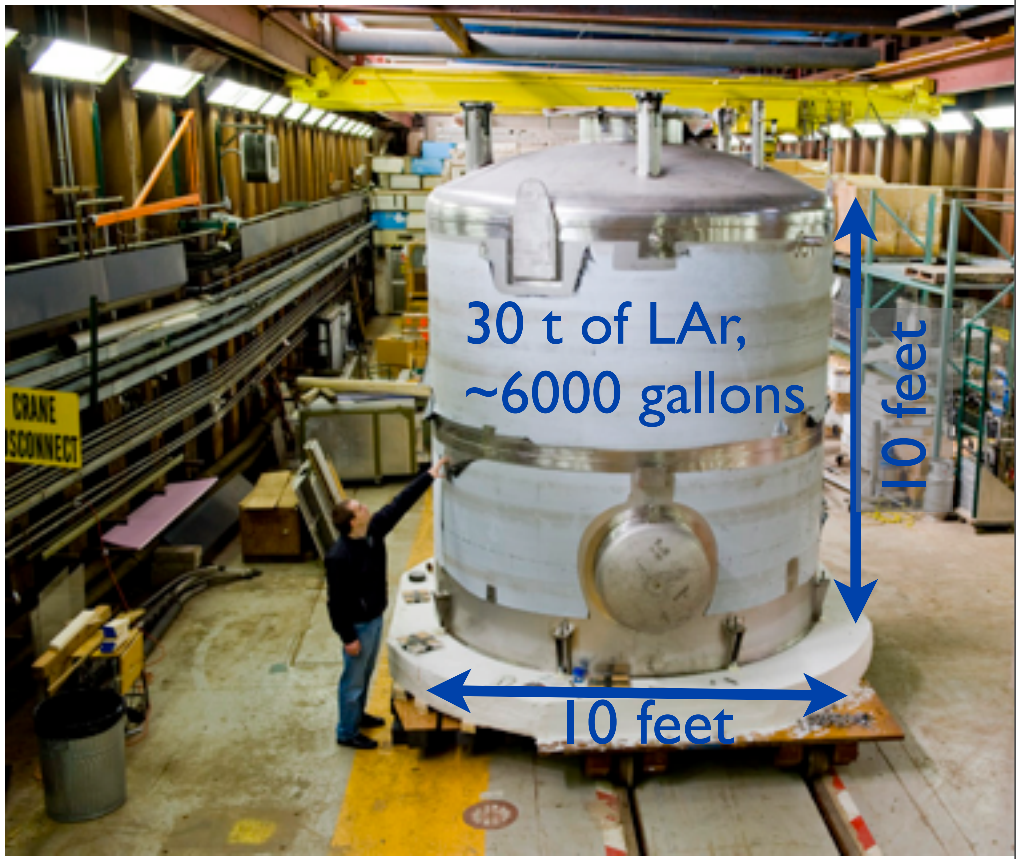
- Removal of electronegative contaminants in a manner that keeps costs low is critical to LArTPC development
- Plot at right shows curves for electron attenuation as function of drift distance
- Acceptable amount of attenuation determined by electronics (S/N)
- Product of lifetime and O2 contamination is 300, empirically determined
- Need $\tau = 5$ ms for 2 m drift distance, or about 60 ppt O_2 equivalent contamination



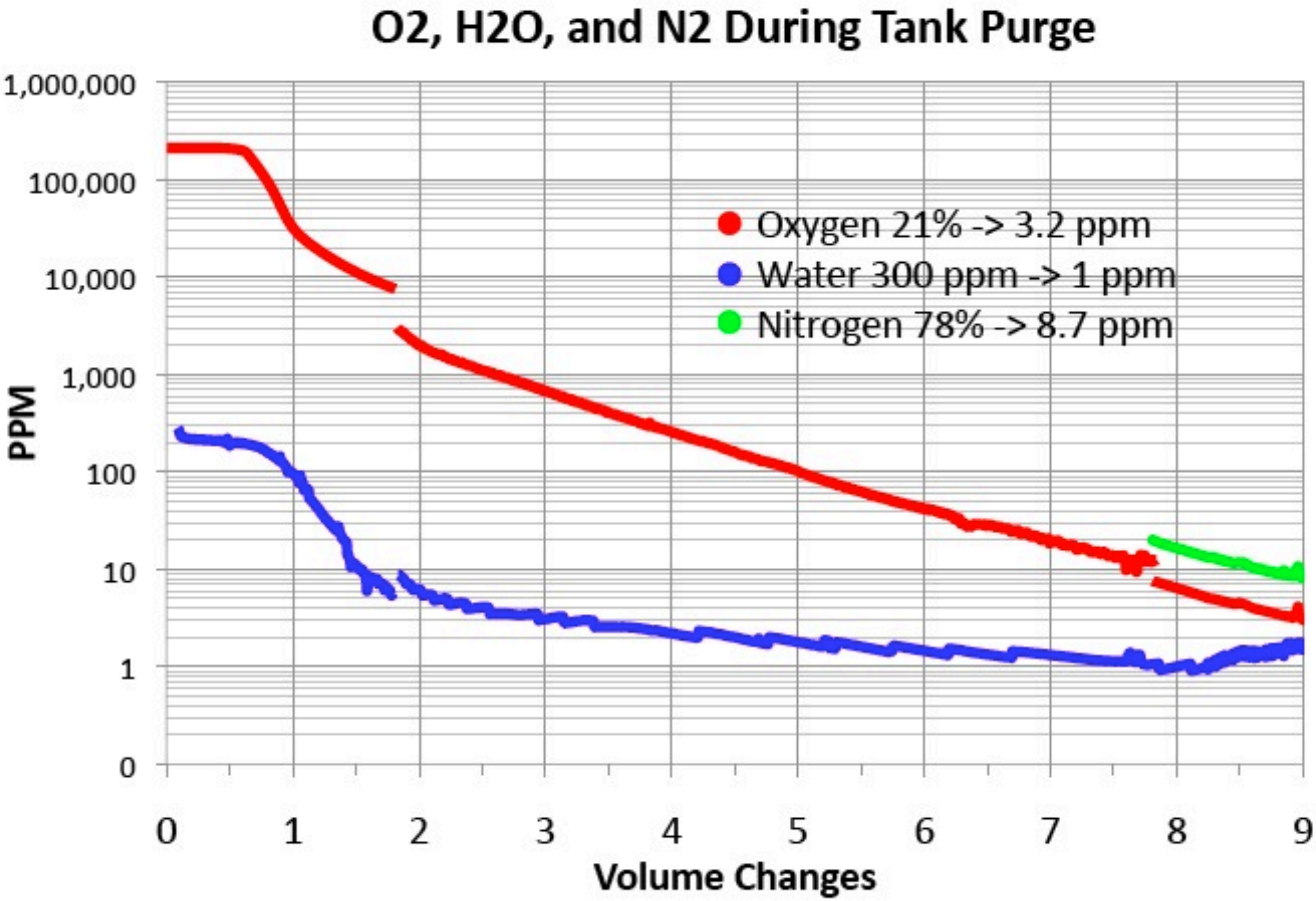
From C. Montanari, June 2007

Liquid Argon Purity Demonstrator

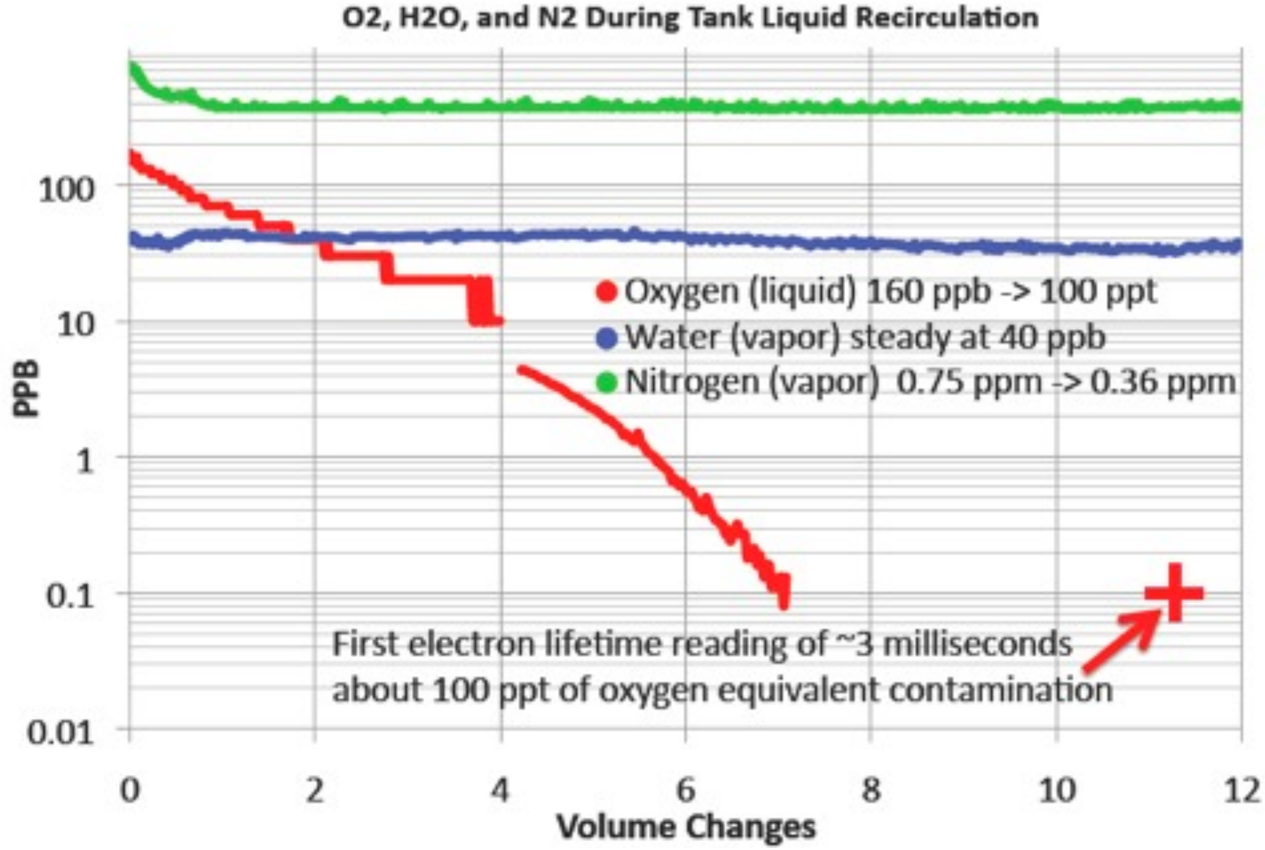
- Primary goal: show required electron lifetimes can be achieved without evacuation in an empty vessel - Phase I
- Also monitor temperature gradients, concentrations of water, O_2
- Phase II will place TPC into the volume and show that the lifetime can still be achieved

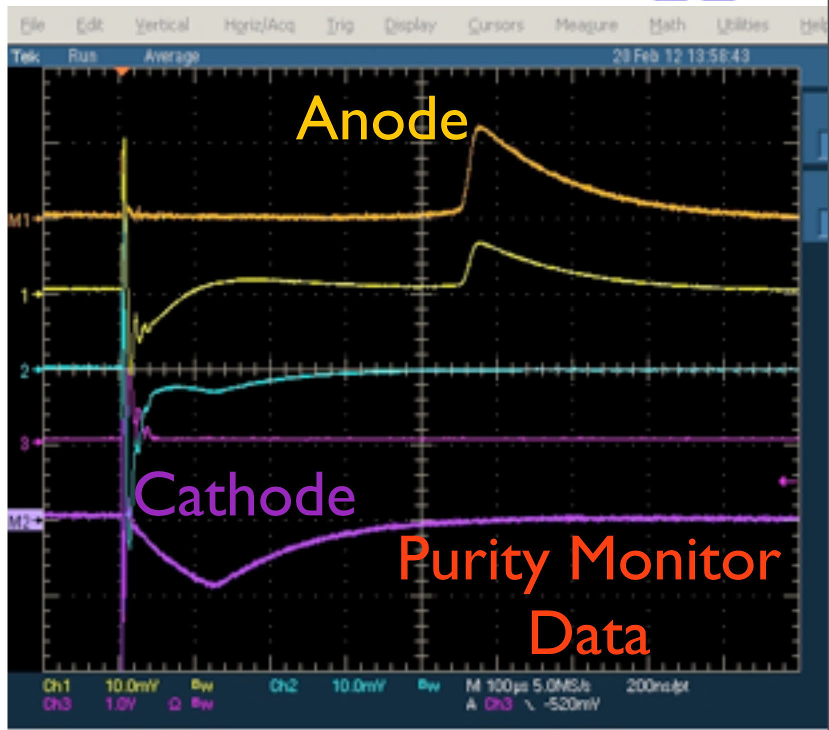


Gaseous Argon Purge



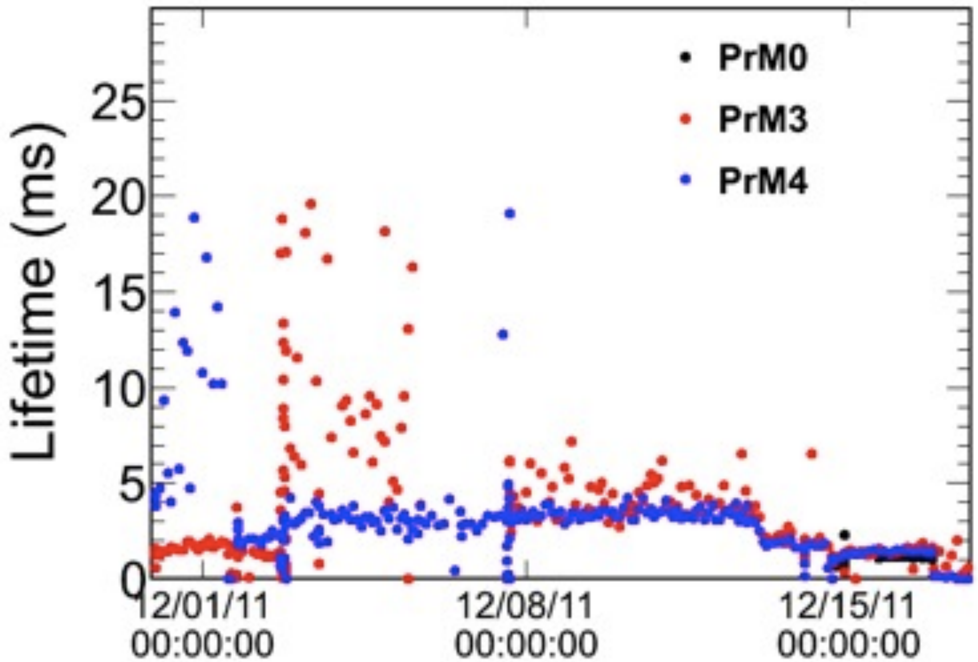
Liquid Argon Recirculation

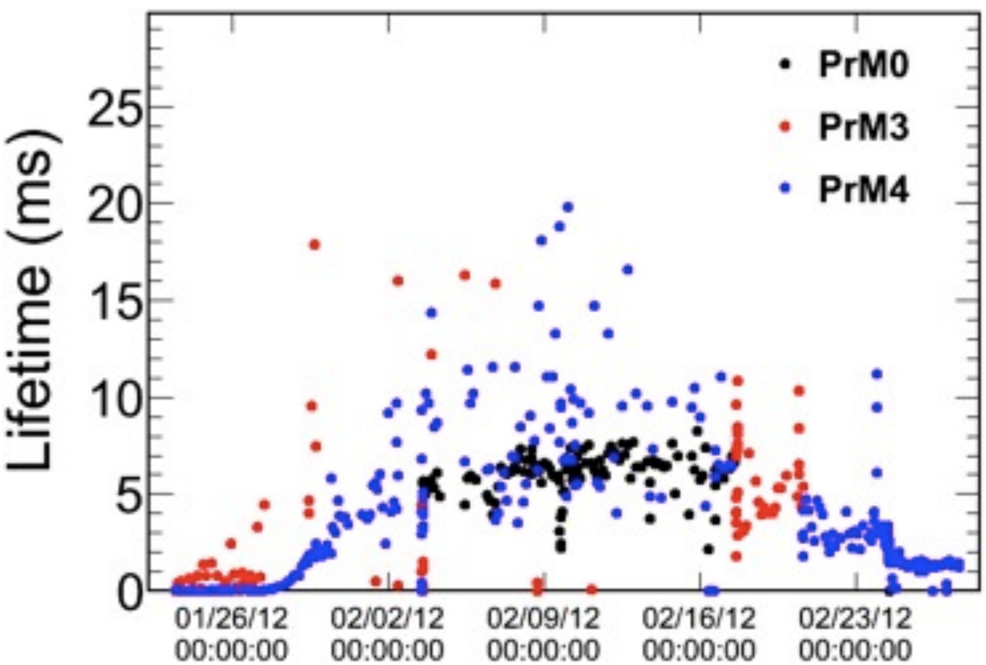




- Liquid filtration began after the flow through the O_2 filter was reversed to prevent clogging of the particulate filters
- Filtration progressed at the rate of about 1 volume exchange every 6 hours
- First electron lifetime measurements made after 11 volume exchanges
- Electron lifetimes were determined to be at least 3 ms, LBNE needs 1.4 ms

Electron Lifetime Stability





- Lifetime during first run was stable at 3 ms or better
- Lifetimes began decreasing after 2 weeks, indicating filter saturation
- Filters were regenerated after the first of the year and running resumed once flow was reestablished with the pump
- Lifetimes went up to 5 ms
- Filters possibly started showing signs of saturation again, but an unplanned power outage stopped the run prematurely
- Currently repairing/upgrading filters and condenser, ready to fill again in June

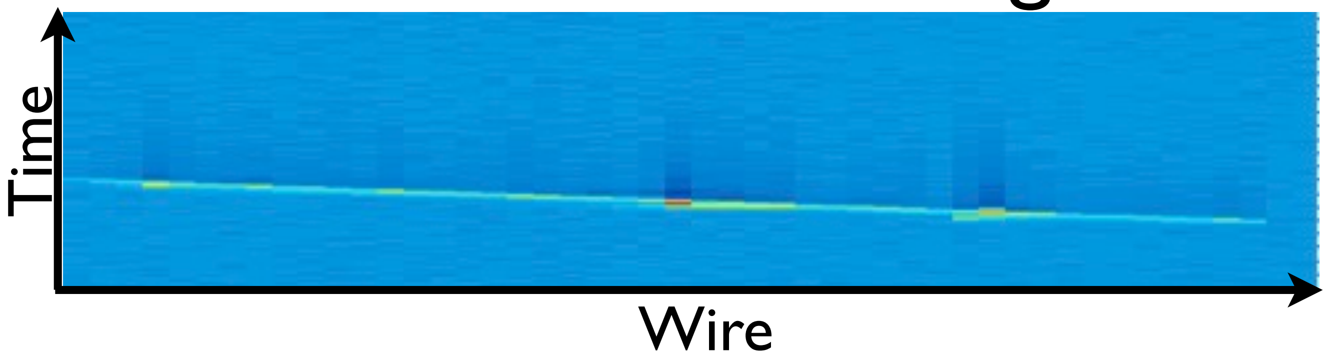
Future Studies

- LAPD will continue running this summer to
  - Fully characterize filter sizing and material performance
  - Study temperature gradients in the bulk liquid as a way to understand convection
  - Study the effect of varying the flow rate on the electron lifetimes
  - Perform studies of how quickly lifetimes can be recovered from intentional poisoning of the environment in the vessel

Cold Electronics

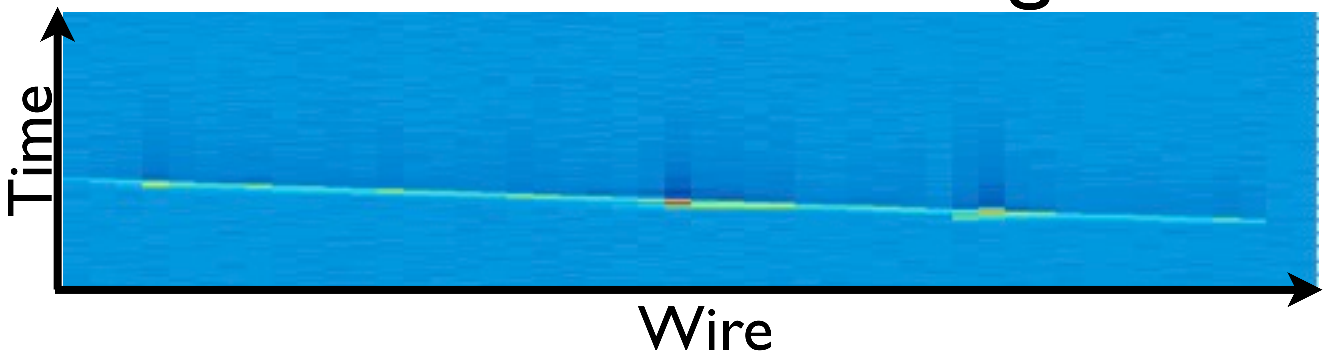
- Large liquid argon TPCs will tens of meters of cable between the readout planes and the data storage
- These long distances can introduce noise and degrade the signal if the preamplifier is outside of the TPC, ie there is significant capacitance between the wire planes and preamps
- Want to instead put the preamps, shapers and signal drivers inside the TPC to minimize the distance and produce as clean of a signal as possible
- There are multiple approaches to using cold electronics currently being developed

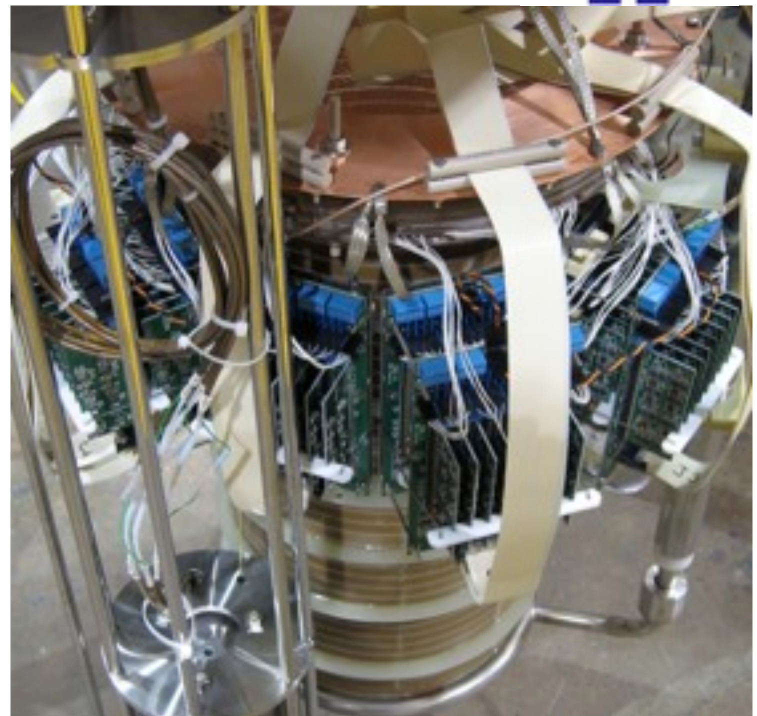
Long Bo

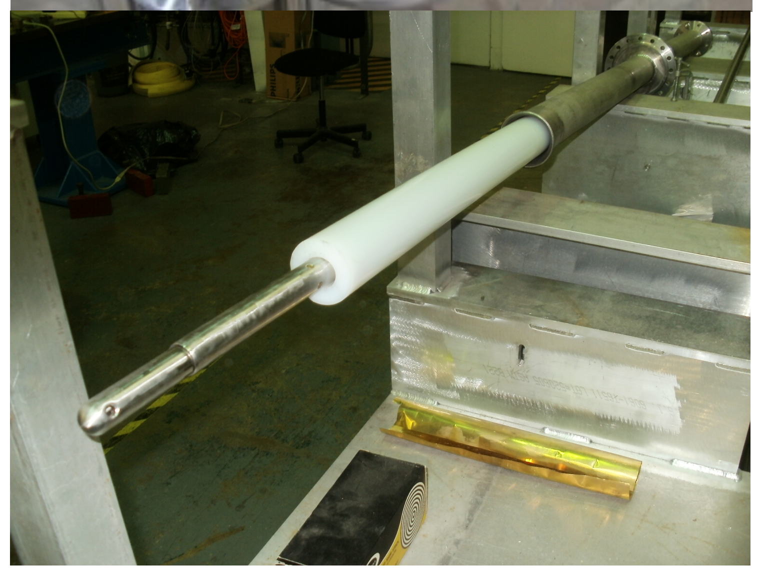


- Long Bo is a cylindrical TPC with 2m drift, it extends the previous Bo test stand TPC
- Will go into LAPD during its second phase
- Long Bo provides the first long drift distance test at Fermilab, has spurred tests of HV feed throughs (100kV) that are benefitting MicroBooNE
- Also extends tests of cold electronics mounted on the TPC, ran twice on Bo in 2011

Long Bo







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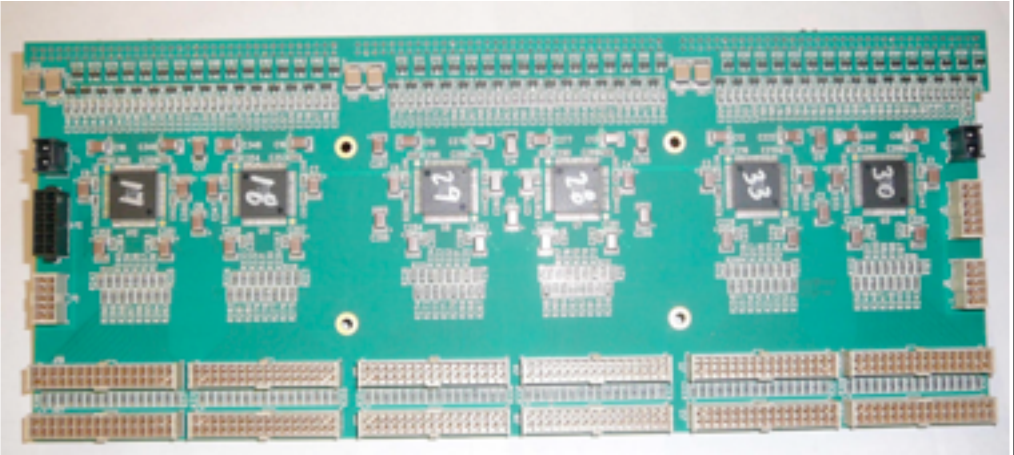
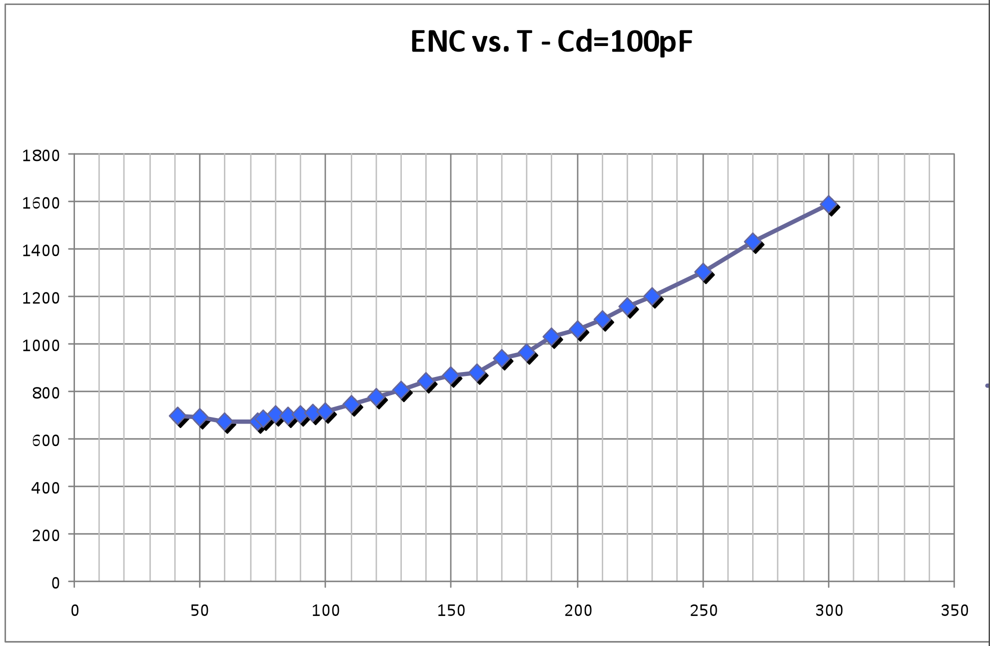
μBooNE: Cold Electronics

- A primary goal of μBooNE is to contribute to understanding of running cold electronics in a LArTPC
- Electronics are being designed primarily by BNL, will be used in LBNE too
- Tests show
  - Noise at 87k is half that at 300k
  - crosstalk and gain variations are each < 0.3%
- Stress tests also performed show no problems after many immersions in LN2
- ATLAS and NA48 calorimeters show very low failure rate over many years





Noise vs Temperature

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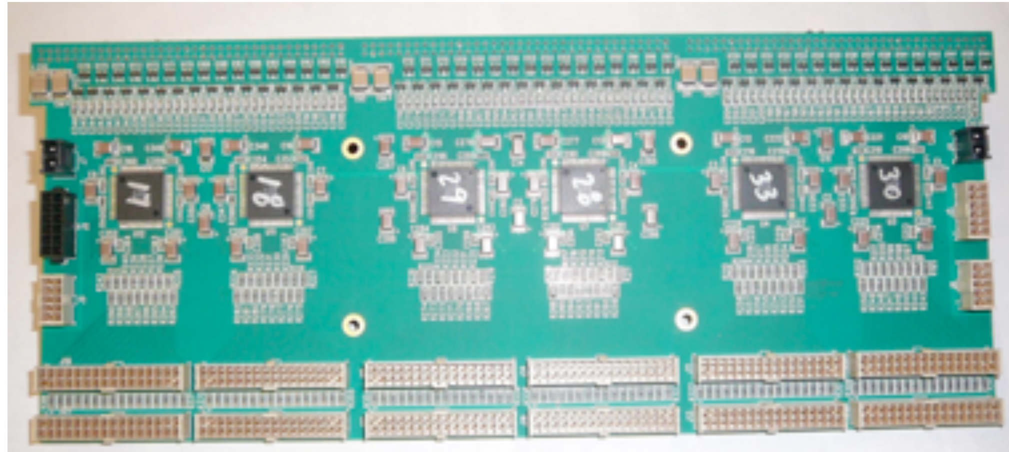
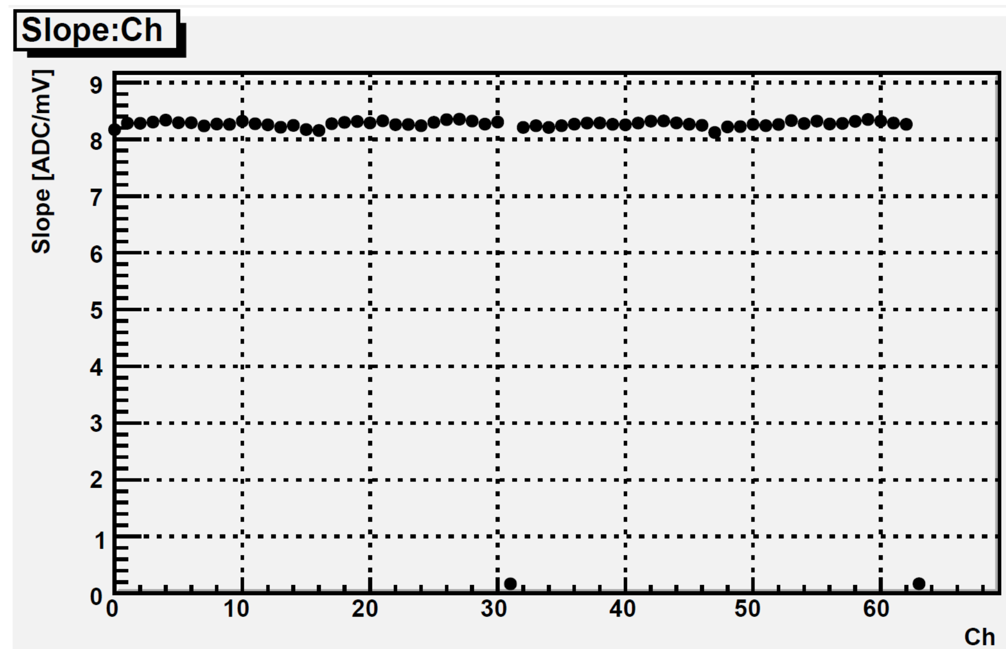
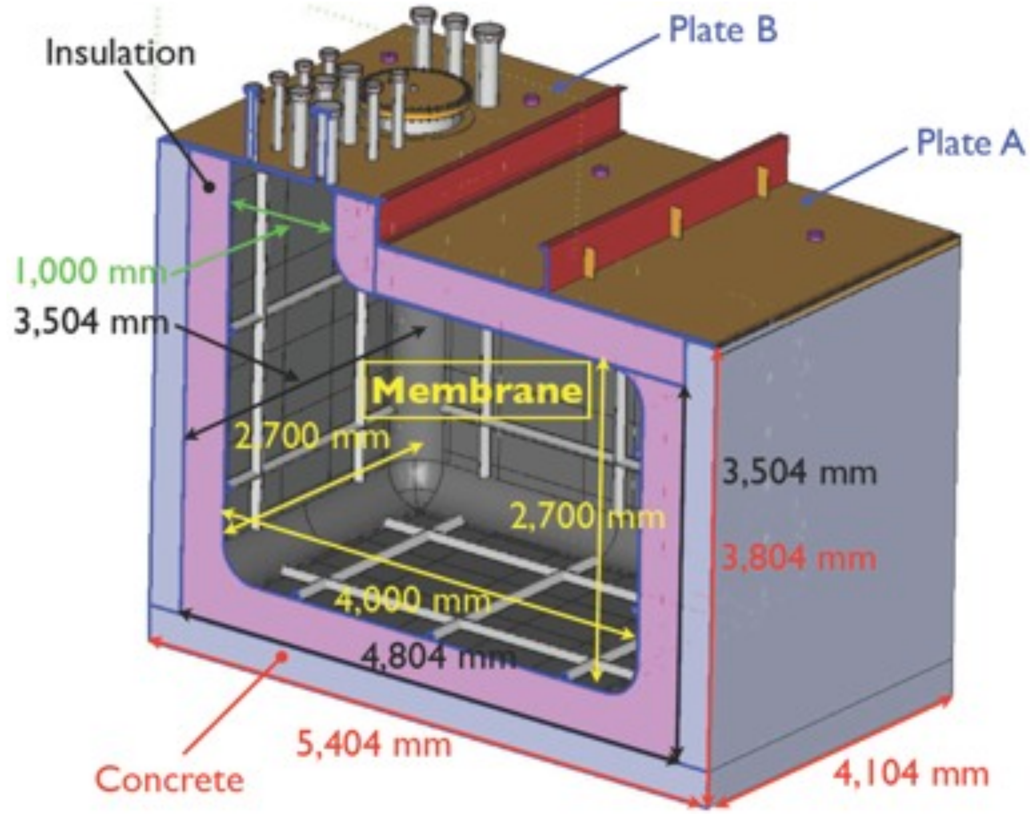


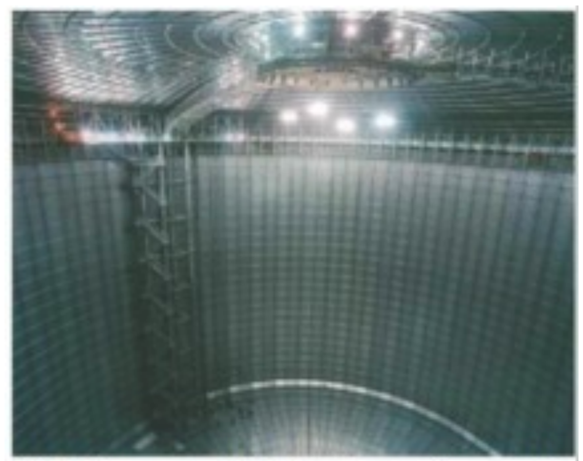


Gain Variation

Cryostat Construction

- Membrane cryostats appear to be a good option for large LAr detectors
- Well understood technology with industry suppliers
- 35 ton prototype will demonstrate thermal performance, leak tightness, and use for LAr
- Will also show there are no issues related to this technology that can affect LAr purity
- Will share LAPD cryogenic filtration and pumping system
- Part of the LBNE project





LNG Storage with Membrane from IHI

35 Ton Membrane Cryostat Prototype

- The concrete bathtub has been constructed
- IHI, the provider of the membrane is at Fermilab teaching technicians and welders how to work with the material

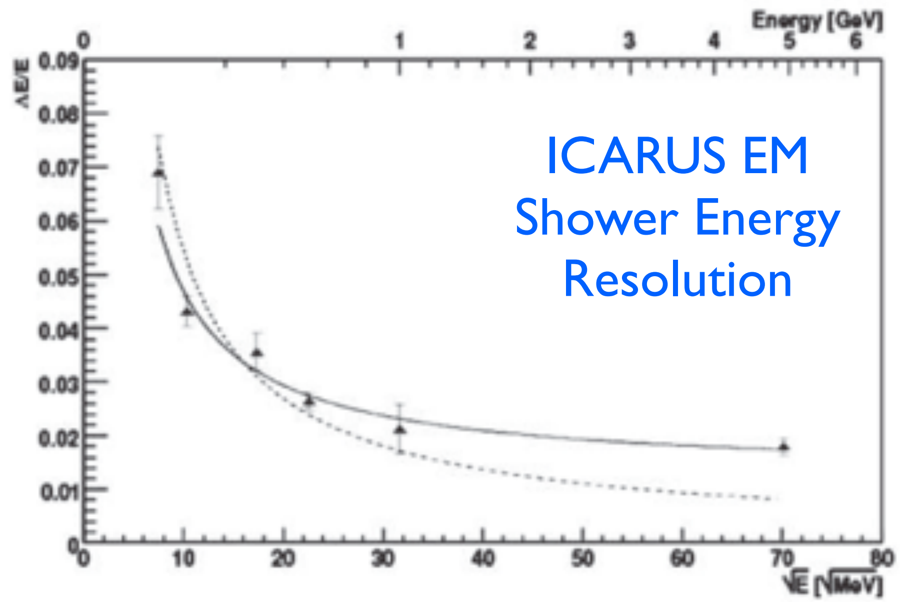
Parameter	Value
LAr Temperature	89K ± 1K
Operating Gas Pressure	70 mBar (~ 1 psig)
Vacuum	No Vacuum, we will SLOWLY purge it with GAr (See LAPD)
Design Pressure	207 mBar (~ 3 psig)
Leak tightness	10^{-6} mBar*l/sec (with NH3 leak check, ASTM standard)
Heat Leak	< 13 W/m² (~11.5 W/m²)
Design Code	Applicable parts of JGA Recommended Practice for LNG In ground storage tanks FESHM 5031.5

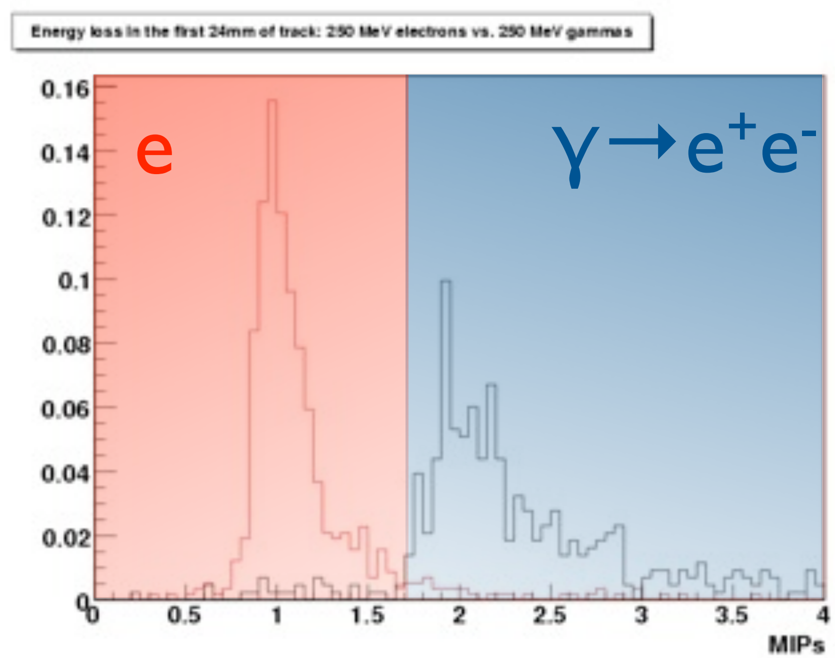
Calibration

- The following are outstanding questions on LArTPC performance
  - EM shower energy resolution
  - Hadronic shower energy resolution, visible vs invisible energy
  - E_{had}/E_{EM} ratio
  - Directionality of through going particles using delta rays
  - Particle identification
  - dE/dx for several particle species
  - Light collection efficiency
  - Surface operation in a high cosmic ray rate environment
  - Studies of proton decay backgrounds
  - Diffusion studies over long drift distances

LAr Detector Beam Test

- Need data from particles and energies expected in neutrino experiments: e, p, π, μ
- Previous estimates of energy resolution from the 50L WARP test stand and ICARUS T600 run on the surface with cosmic rays
- T32 at KEK working to understand charged particles in ArgoNeuT sized TPC
- Need large data set to study e/γ separation in a controlled manner



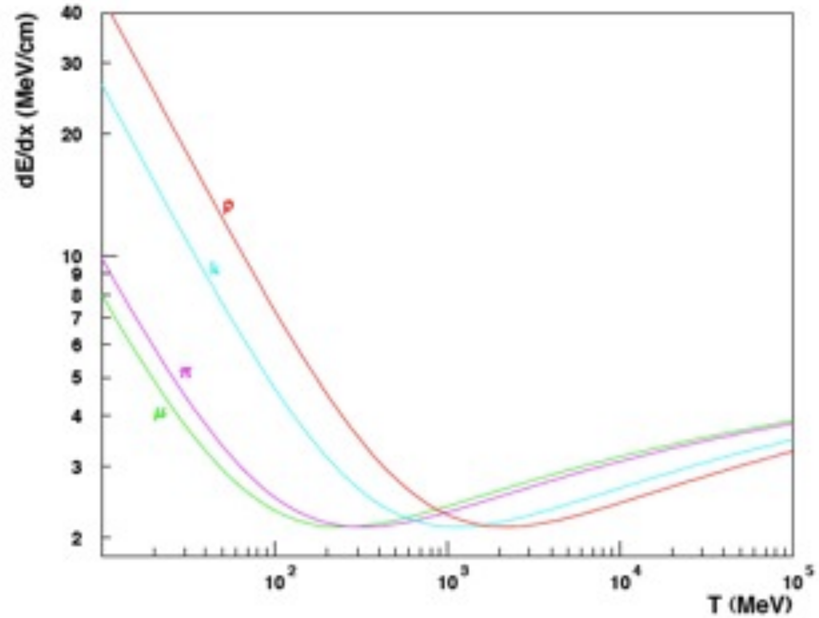


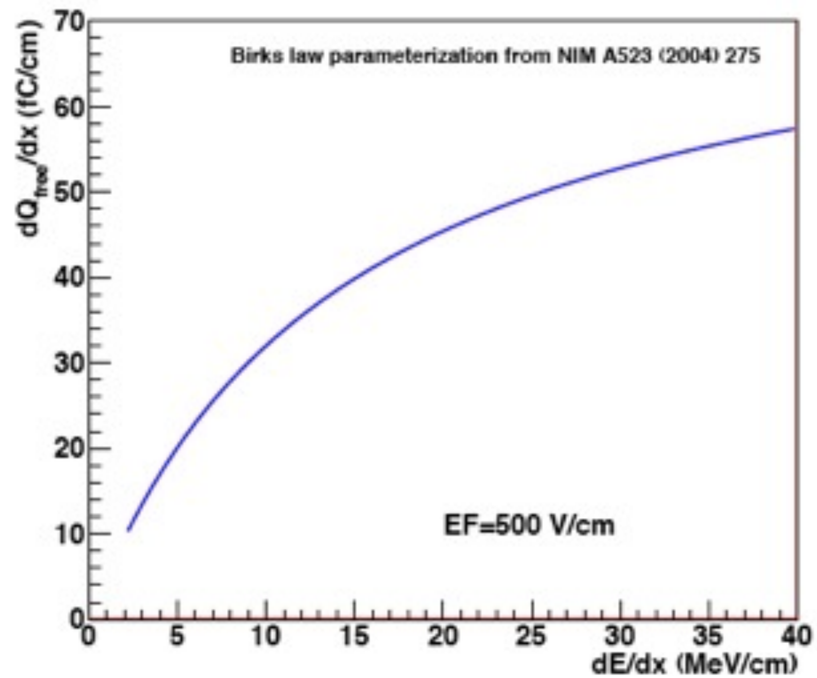
Determining the Right Scale

- Radiation length is 14 cm, need at least 190 cm of LAr in longitudinal direction and 30 cm transverse to contain 95% of the energy
- Hadronic interaction length is 80 cm, need 240 cm of LAr longitudinally and up to 160 cm transversely
- Muons lose 2.2 MeV/cm, so a 5m long active volume will range out a 1 GeV muon
- TPC should have active volume on the scale of 1m x 1m x 5m
- Studies to optimize the size are underway

Phased Plan

- We would like to get started on understanding the calibration as quickly as possible
- Yale and Syracuse have submitted a NSF proposal to upgrade ArgoNeuT
- Will be used to study charge to energy conversion with single track topologies
- Also will study initial ionization in EM showers to understand e/γ separation
- Second phase is to build a facility for the larger scale TPC discussed on the previous slide
- Larger facility will tackle the remaining questions





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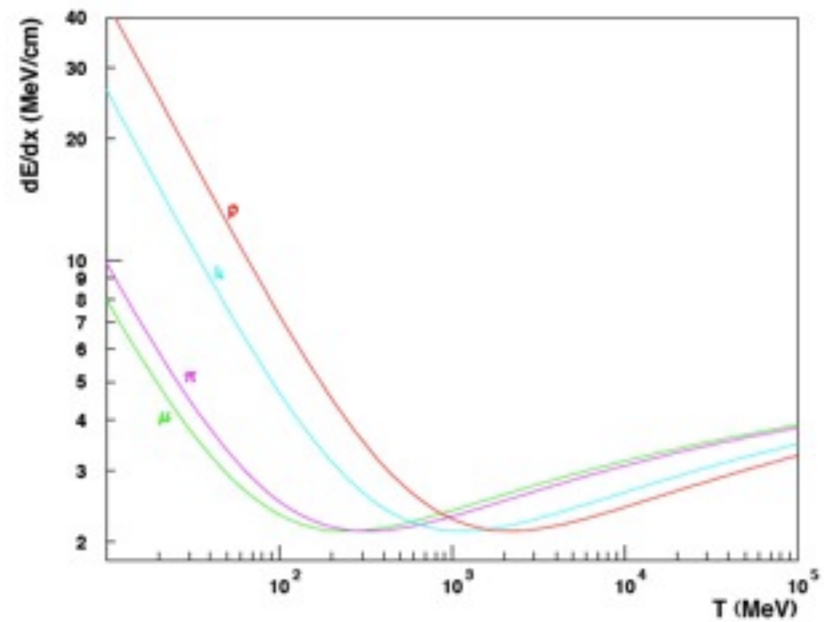
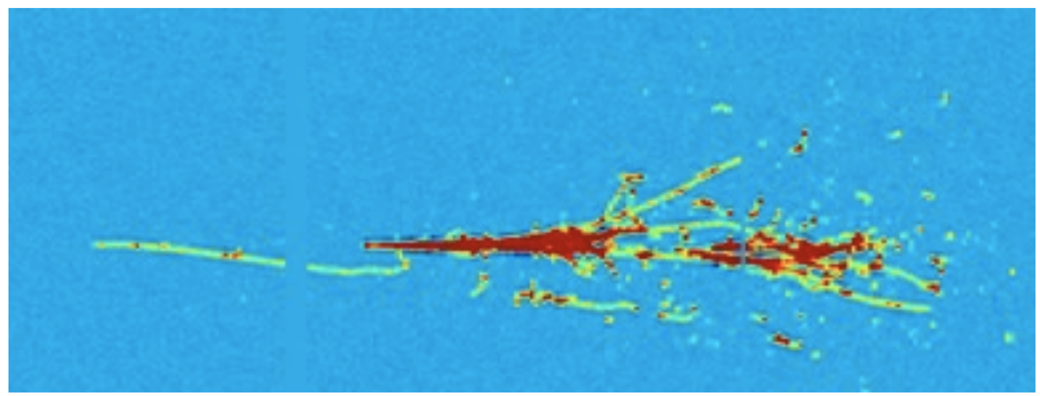
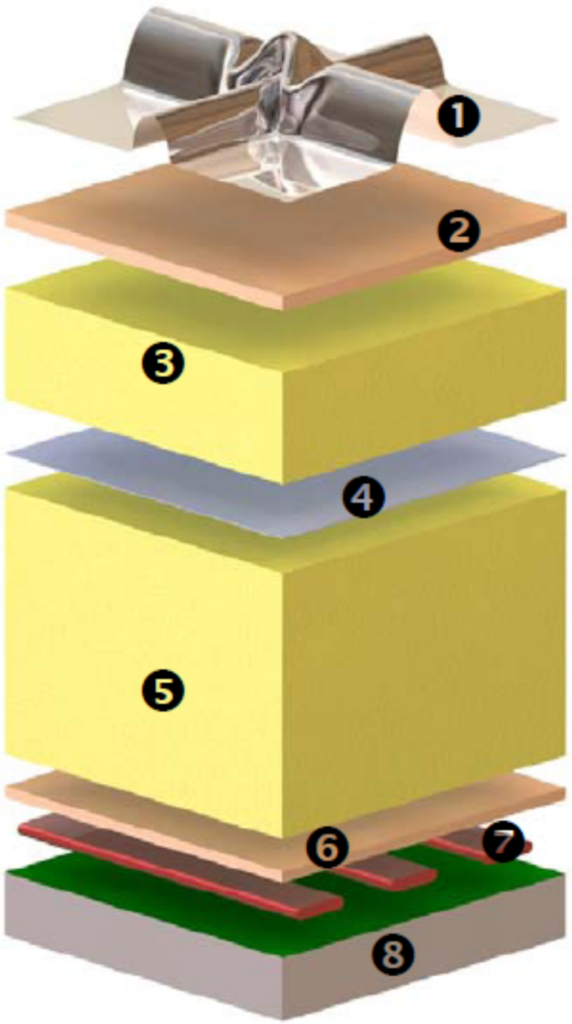




Summary

- Primary challenges to developing large liquid argon TPC are identified and program developed to address them
- LAPD showed for the first time that an electron lifetime well above that needed for LBNE can be achieved without evacuating the vessel
- The Long Bo test of large drift distance TPCs will go into LAPD for its next run
- The 35 ton membrane cryostat prototype is currently under construction with help from IHI to develop institutional knowledge at Fermilab
- MicroBooNE is contributing to understanding cold electronics as well as purity measurements and proton decay backgrounds
- The liquid argon detector beam test effort is underway and has good collaboration between university groups and national labs

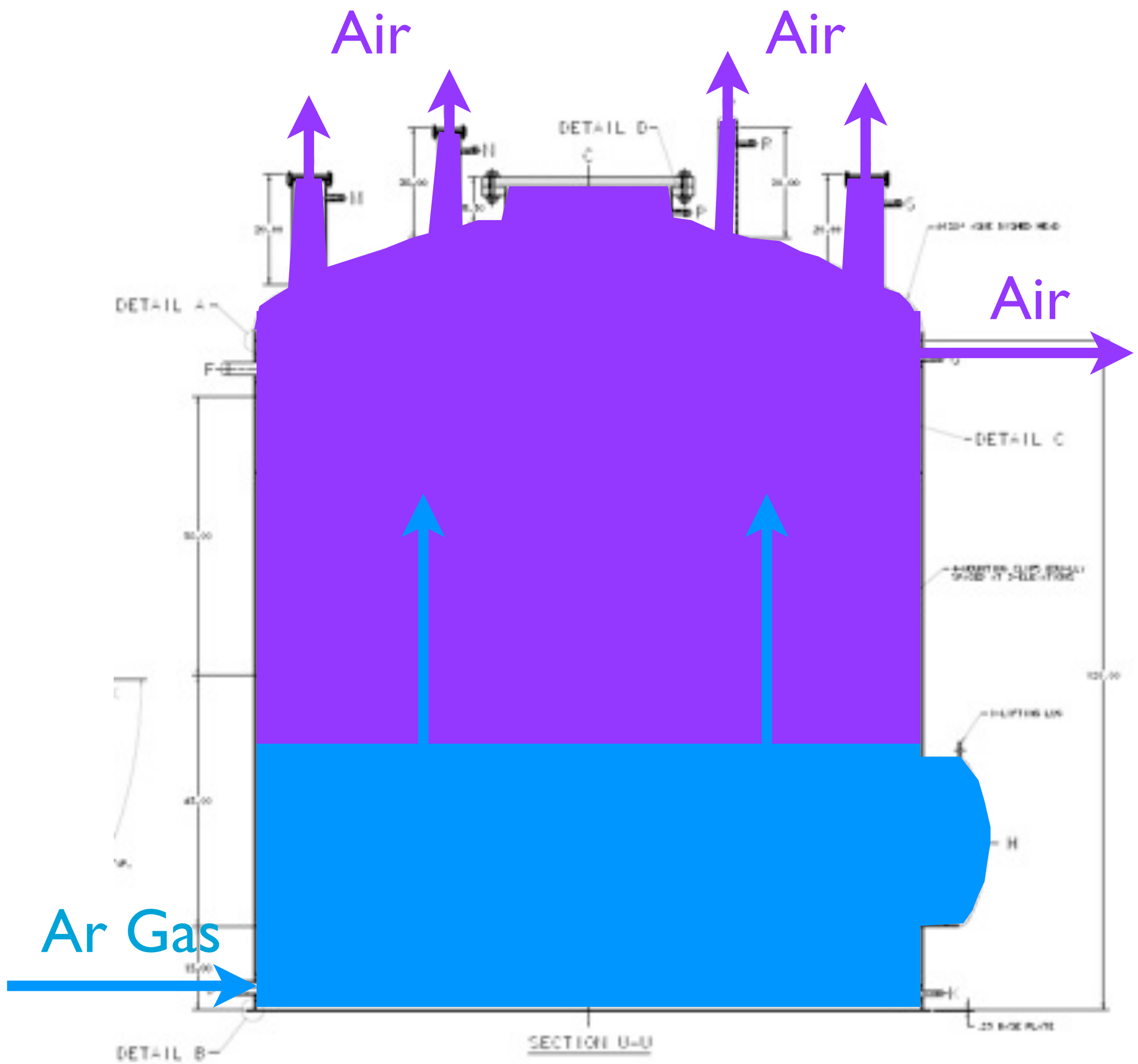
Membrane Cryostat



1. Stainless steel primary membrane
2. Plywood board
3. Reinforced polyurethane foam
4. Secondary barrier
5. Reinforced polyurethane foam
6. Plywood board
7. Bearing mastic
8. Concrete covered with moisture barrier

Phase I - Purification without Evacuation

- Basic idea is to use an argon piston for initial purification, followed by a few more volume exchanges
- Cycle a few volumes of clean, warm Ar gas through the volume to push out ambient air and dry out surfaces
- Then recirculate the gas through filter system when contamination is < 50 ppm



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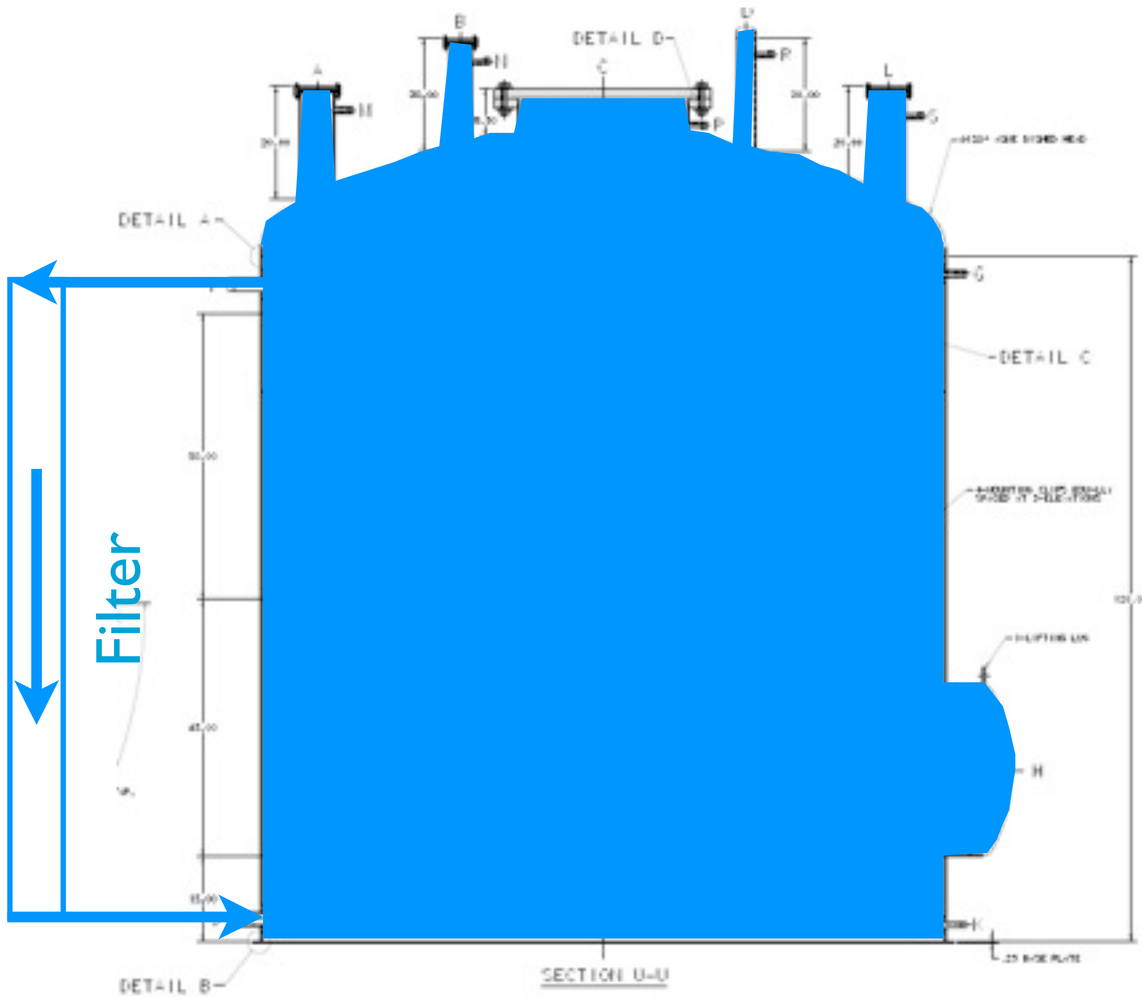
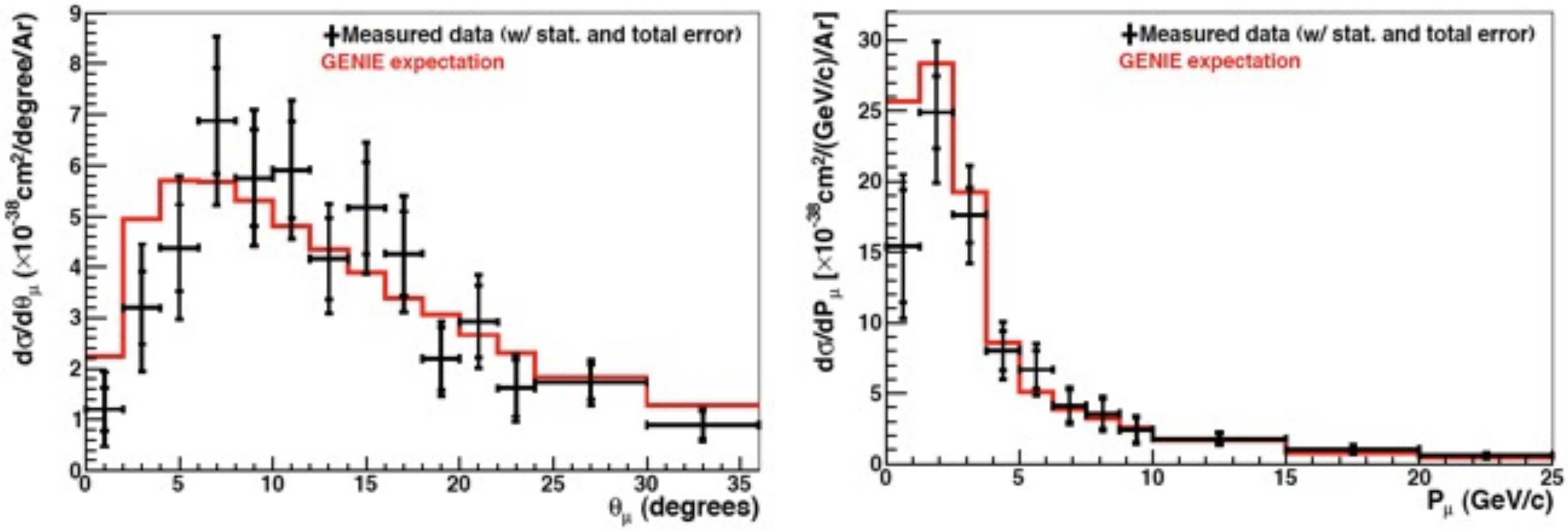


ArgoNeuT: First Cross Section Measurements on Ar

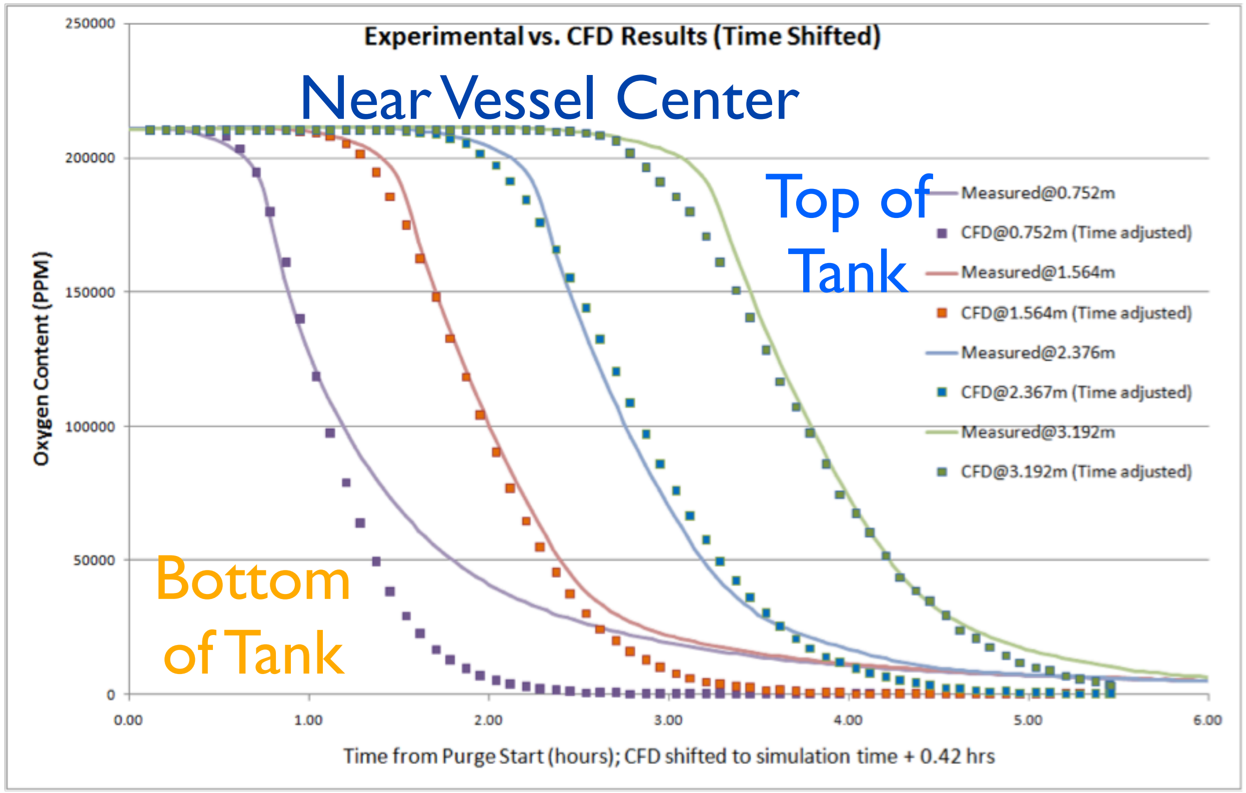


- ArgoNeuT took data in NuMI beam for 5 months in 2009-2010
- First measurements of differential cross sections for neutrino-Ar interactions made with the neutrino mode data

$$\sigma/E_\nu = (7.3 \pm 1.2) \times 10^{-39} \frac{\text{cm}^2}{\text{GeV}} \quad \langle E_\nu \rangle = 4.3 \text{ GeV}$$

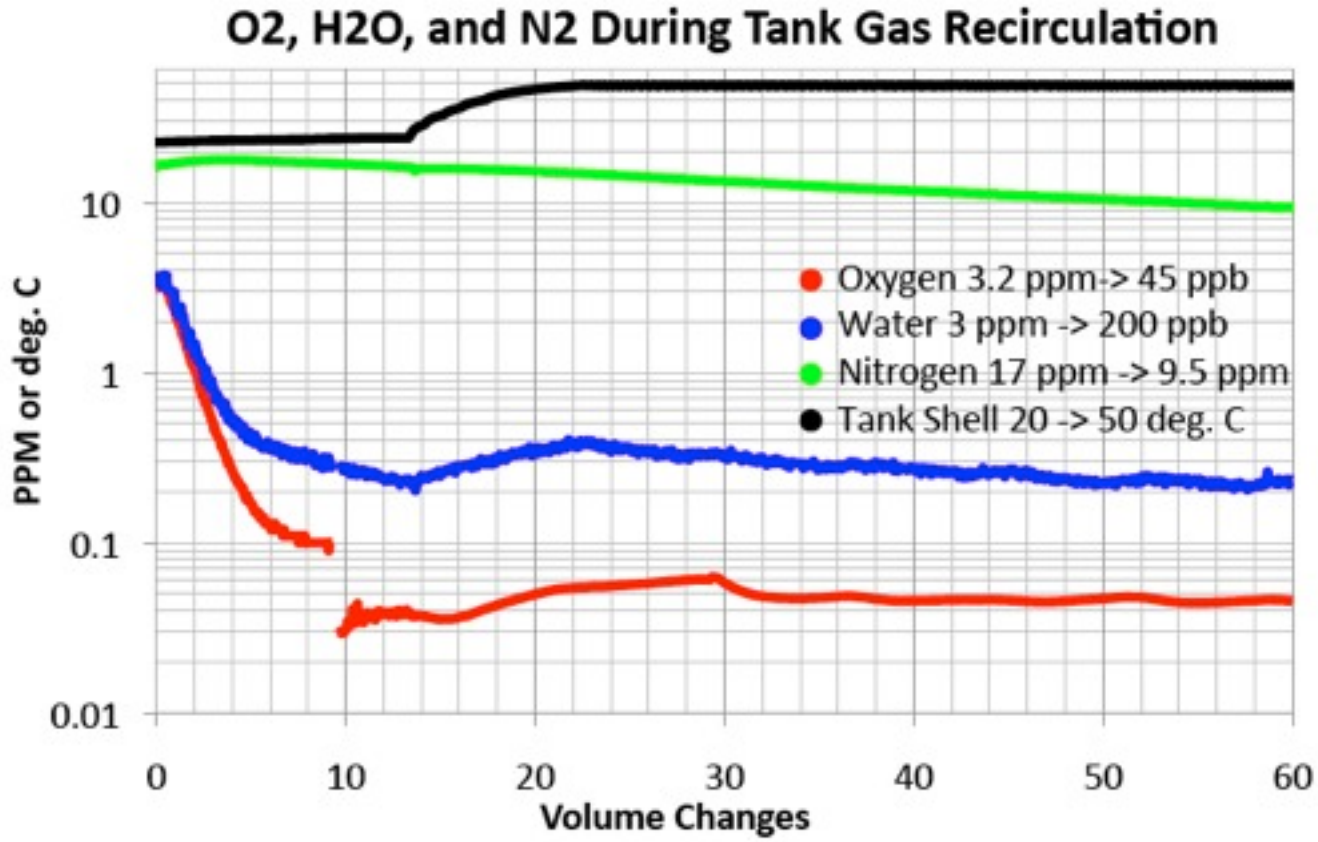
- Published in PRL 108, 161802 (2012), 2 more papers nearly ready for submission to journals
- Collaboration between Fermilab and 8 other institutions

Gaseous Argon Purge



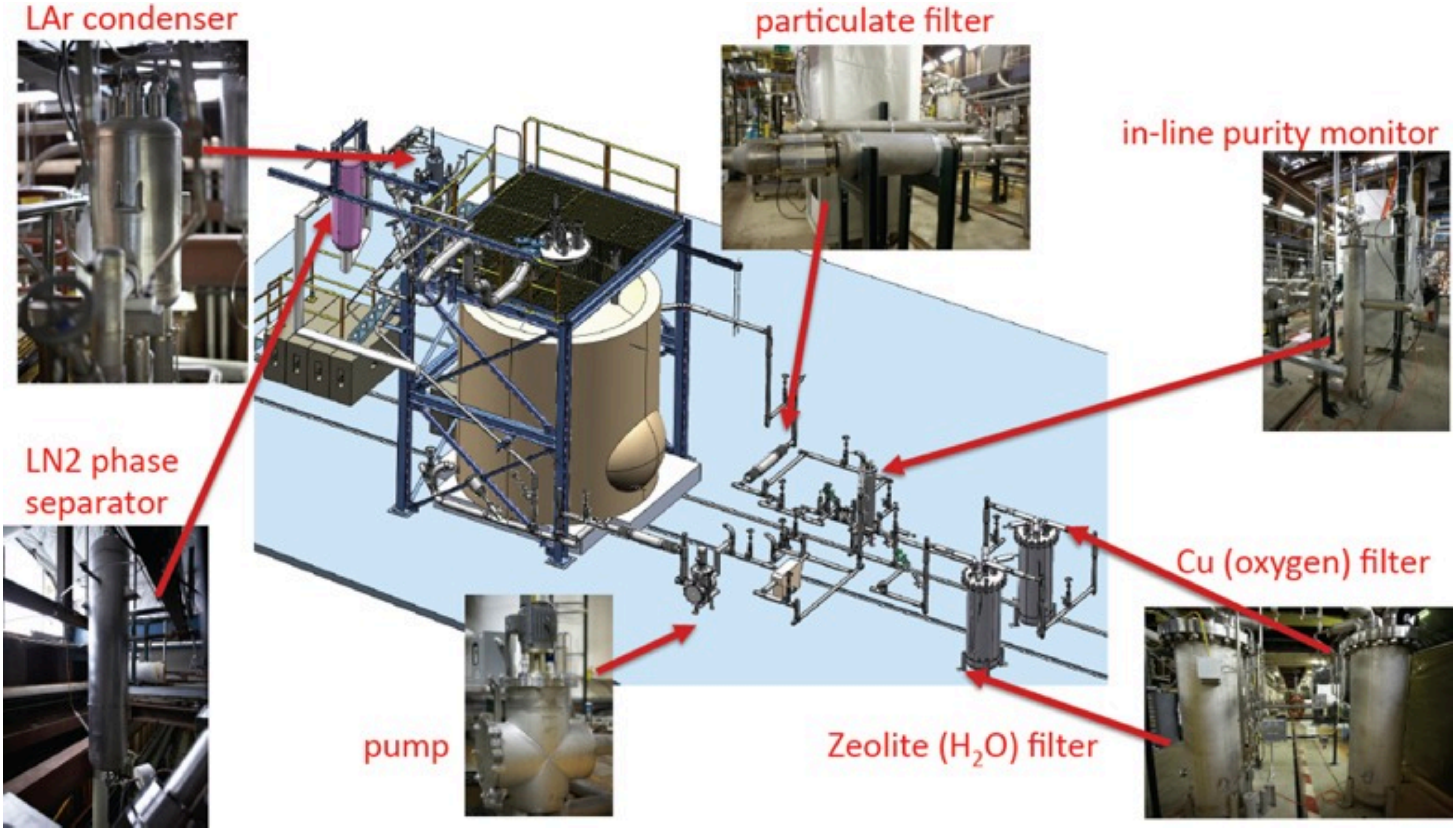
- Set of sniffer tubes monitored the oxygen content of the gas inside the vessel at various depths throughout the purge
- Plot shows the content relative to the pre-purge state of the tank in solid lines
- Clear front of argon gas moving through the vessel
- Comparison to calculations (points) shows good agreement, aside from some discrepancy in time that is likely due to 3D flow and mixing as argon gas is forced into the bottom of the tank

Gaseous Argon Recirculation



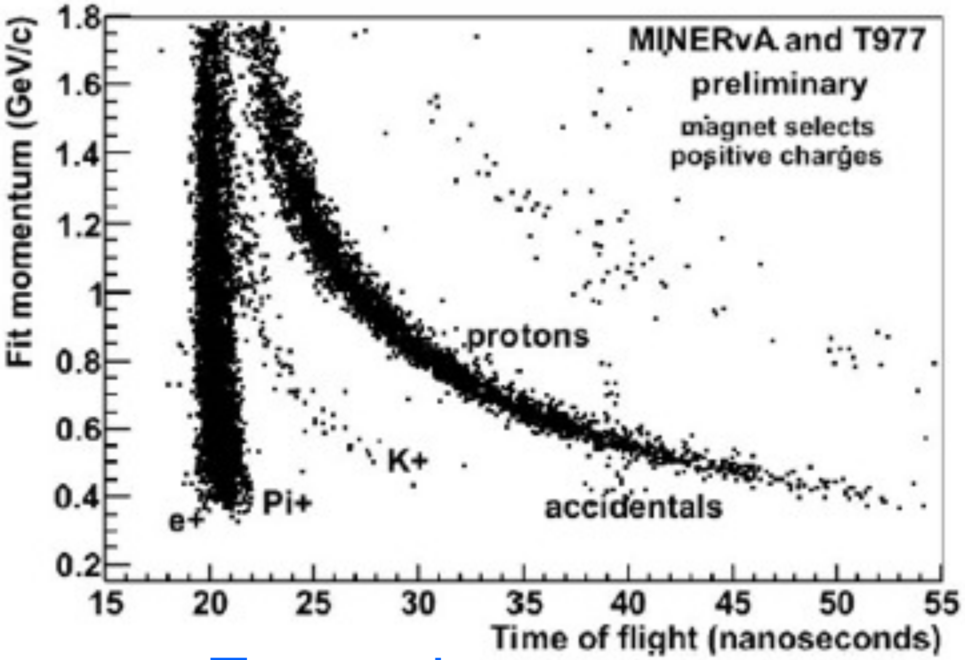
- The purge was very successful and brought the vapor in the tank to a contamination level that was below the specifications for the delivered liquid
- Both O_2 and H_2O contamination were well below 1 ppm after 3 volume exchanges
- Maintained sub-ppm levels in the gas for over 20 days
- Heating the tank shell allowed more contamination to be "baked" out

System in 3D


LAr condenser
particulate filter
in-line purity monitor
LN2 phase
separator
Cu (oxygen) filter
pump
Zeolite (H_2O) filter

The Plan

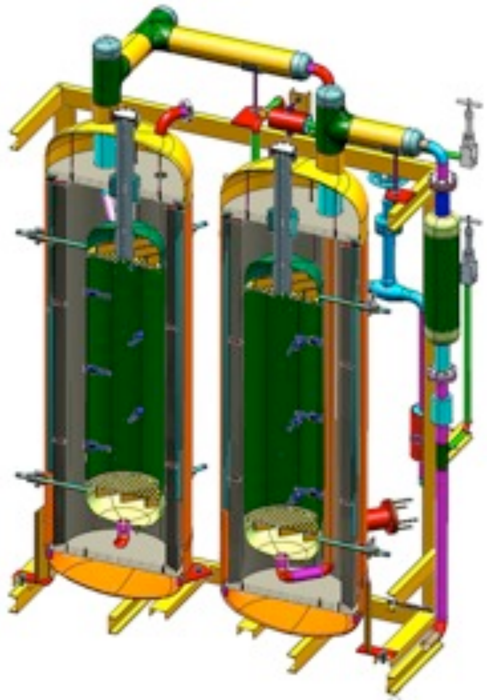
- We would like to create a facility for long term use where we can have the most flexible program both in terms of calibration tests and R&D related tests
- We have examined both the M-Test and M-Center areas in the Fermilab Test Beam Facility
- M-Center appears to be the better of the two locations
- Size is better matched to the goals and it can be made available for an extended amount of time
- Would make use of the tertiary beam setup that was first used in the MINERνA test beam program

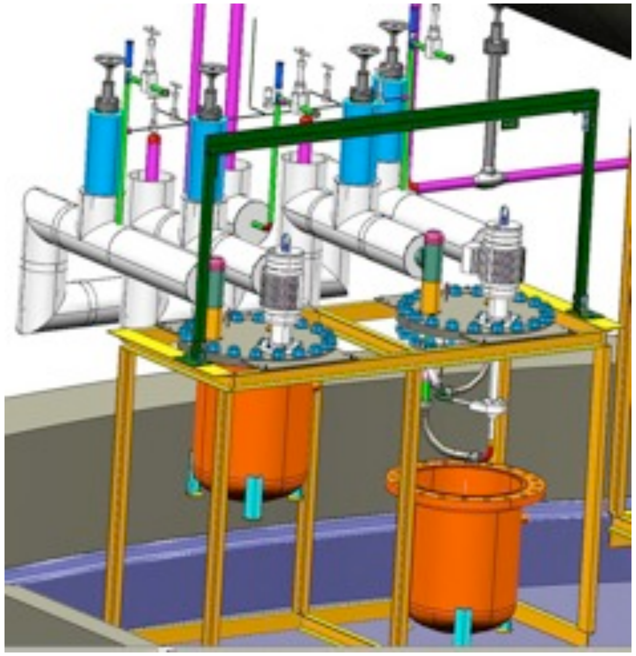


Tertiary beam composition

Phase 2: The Facility

MicroBooNE
Filter Skid





MicroBooNE
Pump Skid

- Fermilab would provide the facilities, other groups would provide the active detectors
- The facility will provide a filtration and pumping system that is appropriately sized to the volume of LAr
- Use experience from LAPD and MicroBooNE for cryogenic system design
- Build cryostat to allow convenient access to inside of vessel
- Imagine exchanging electronics, light collection systems, TPCs, etc during several year program

Institutions Expressing Interest in the Beam Test